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INTRODUCTION TO LAKE CURRENT STUDIES

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In this study of currents in Lake Michigan, the variations in physical characteristics, temperature and density, of water within the lake is determined, and the water movement patterns over a period of time are measured. From considerations of cause and effect, a theoretical basis for generalizing the observed conditions is developed. This information is to be used to assist in predicting the fate of pollutants introduced into the lake and to assess the effects of waste inputs on lake water quality.

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U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Division of Water Supply and Pollution Control
Great Lakes-Illinois River Basins Project

TABLE OF CONTENTS

	Page
INTRODUCTION	1
DESCRIPTION OF THE LAKE	2
GENERAL CONSIDERATIONS	3
Diffusion	3
Turbulent Mixing	3
Advection	6
Meteorology	8
Possible Fate of Pollutants	8
PROCEDURES	11
Temperature Studies	11
Tracer Methods	12
Fixed-Position Current Metering	12
REFERENCES	13
FIGURES	

FIGURES

1 Drainage Basin of Lake Michigan

2 Current Meter Station

3 Chicago Cribs and Beaches

4 The Bathythermograph Slide

INTRODUCTION

A study of currents in Lake Michigan is part of the overall program of investigations undertaken by the Great Lakes-Illinois River Basins Project. The ultimate objectives of the studies are: to assist in predicting the fate of pollutants introduced into the lake; to assess the effects of waste inputs on lake water quality--effects both local and area-wide, both for now and in the future; and to aid in the making of wise decisions for protecting this valuable water resource.

The dispersal of waste-bearing waters from a point of input to the lake is accomplished by some combination of three processes: 1) molecular diffusion, 2) turbulent mixing, and 3) mass transport. The relative importance of each process will depend on physical conditions in the lake. For example, in completely quiescent waters the predominant process would be molecular diffusion. Turbulence (the existence of randomly-varied water velocities) in the vicinity of the point of input will greatly accelerate the rate of dispersal over that effected by molecular activity alone. If, superimposed on this random turbulence, there is a prevailing velocity, then the water mass as a whole, and the accompanying waste waters, will move in that direction. Knowledge of the existence (or absence) of such movements is essential, both for predicting the fate of pollutants and for planning strategic locations of waste input and water takeout points to minimize short-circuiting.

The objectives of the Lake Michigan current study are, then: to determine the variations in physical characteristics, temperature and density, of water within the lake; to measure the water movement patterns over a period of time; and to develop, from considerations of cause and effect, a theoretical basis for generalizing the observed conditions.

DESCRIPTION OF THE LAKE

Lake Michigan ranks fifth in size of all the fresh water lakes in the world and third in size of the Great Lakes of North America. By comparison the lake is equivalent in area to the State of West Virginia; however, its bottom is not characteristic of a hilly or rugged terrain. The lake has a surface area of 22,400 square miles, a maximum depth of 923 feet, and an average depth of 276 feet. The deepest portion of the lake is nearly 343 feet below sea level. It is 307 miles long and 118 miles wide, measured at the wide point through Green Bay.

The shoreline length, including islands, is 1,660 miles. The drainage basin, land and water area, covers 67,900 square miles (Figure 1). The volume of water in the lake is 1,170 cubic miles.

The mean water surface elevation of Lake Michigan is 578.80 feet above sea level. The range of monthly means about the mean elevation is 6.3 feet and the average seasonal (difference between summer and winter) fluctuation is 1.0 foot.

Historically the total annual diversion from Lake Michigan into the Illinois River Basin has varied markedly in different periods, as shown below (1).

Average	1901-1939 (water years - Oct. 1 thru Sept. 30)		7210 cfs
"	1940-1961	"	3240 cfs
"	1901-1961	"	5750 cfs

Outflow through the Straits of Mackinac is 40,000 cfs (1931-1960). This has been computed by the tributary inflow plus precipitation minus evaporation. Tributary inflow as estimated by the U.S. Geological Survey is 38,900 cfs (1).

The U.S. Lake Survey, Detroit, Michigan has computed the precipitation on the lake surface from adjacent land stations. The estimate of the average annual precipitation from 1900 to 1960 is 30.4 inches (2). Evaporation from the lake as estimated by the U.S. Weather Bureau is 27.8 inches (3).

GENERAL CONSIDERATIONS

In order to comprehend the details of the data on currents it is logical to review the theoretical concepts and the terminology of the study.

A pollutant which is a liquid or a suspension of small particles, when introduced into a body of water, may be diffused (molecular scale), mixed or diluted (larger scale), and advected or moved by currents (still larger scale). All three scales of motion are present in Lake Michigan. Each will be discussed in turn and its significance considered. It will be evident by the end of the discussion that there are many gaps in our knowledge of these forces. Some of these gaps can be filled by a field investigation; the rest await advances in theory and instrumentation.

Diffusion

Molecular diffusion is a complex random motion directly associated with molecular motion and accelerated by the thermal agitation of individual molecules. It is perhaps the least important motion for pollutants in Lake Michigan in comparison with the effects of larger-scale movements. Other than acknowledging its existence, molecular diffusion will not be considered further.

Turbulent Mixing

Turbulent mixing is a complex random motion <u>not</u> directly associated with the agitation of individual molecules. According to Corrsin (4), "....turbulence can be expected in a fluid whenever there is a shearing flow and the inertial effects are much larger than viscous effects." These conditions are often satisfied in Lake Michigan. Turbulence affects the dispersal rate of pollutants much more than does molecular diffusion.

Generally speaking, "....much of the core of the turbulence problem has yet to yield to formal theoretical attack" (4). Mathematical difficulties in handling non-linear expressions have greatly hampered progress; the non-linearity implies that there are no simple relationships readily susceptible to mathematical treatment. Work relating to natural waters, both salt and fresh, has been published by Richardson and Stommel (5), Stommel (6), Joseph and Sendner (7), Noble (8) and others. In addition, there is significant unpublished work by Schonfeld of the Netherlands and Okubo of the Johns Hopkins University's Chesapeake Bay Institute, among others.

The wind, acting both directly and indirectly, appears to be the chief force causing water motion in Lake Michigan. It is the chief force overcoming inertia and stability, resulting in internal turbulence. Wind stress on the water surface can cause waves, set-up, and currents, and if abruptly terminated after a sufficiently long period, may result in a seiche.

If water temperatures are vertically isothermal, the wind could stir the whole lake. Wind results in waves and orbital particle motion to depths of at least half a wave length if thermal stratification is not too strong. If the wind blows from the same direction for a few hours, it will cause set-up; that is, wind stress will drag surface water to the leeward side of the lake, causing a measurable piling up of water against the shore. Mixing will occur while water is moving toward the shore and while part of the piled-up water is escaping by moving parallel to the shore or by reverse flow as a subsurface current. In addition, when the wind either stops blowing or shifts direction, the piled-up water begins to return to the opposite side of the lake. Often it surges back and forth across the lake several times with a period determined by basin geometry and fluid density; this phenomenon is called a "surface seiche." The seiche, of course, results in further, though less important, mixing. To increase the complexity of the matter, if there is significant density stratification, an "internal seiche" may be started. The internal seiche, like the surface seiche, is a wave form at a density interface, though in this instance there is water above and below, while for the surface seiche air is above and water below. Periods of internal seiches are longer and amplitudes are very much greater (10 times and 1000 times, respectively) than surface seiches. Because of the large amplitudes, internal seiches can accomplish more mixing. Seiches may be uni- or multi-nodal. The possibility of their presence makes a single temperature observation suspect; observations should be repeated at each location to ascertain conditions. Observations off Chicago by Project personnel in October 1961, indicated a 23-foot vertical movement of an isotherm within $3\frac{1}{2}$ hours. If such motion is typical, attempts to estimate the volume of water available for mixing in the epilimnion (or upper layer) without a set of simultaneous temperature-depth measurements could be disastrously in error.

It is pertinent to insert a discussion of the Lake Michigan temperature structure here, because temperature structure determines density structure which in turn determines stability. The most important published works are by Van Oosten (9), describing data from 136 stations occupied from mid-April to mid-November in the years 1930, 1931, and 1932; by Church (10), describing 2,000

bathythermograph soundings made between November 1941 and February 1944; and by Ayers, et al. (11), describing four synoptic* studies of 50 or more temperature stations occupied in June and August, 1958.

During early winter months the lake surface cools and convective mixing occurs as the denser colder water sinks. This mixing may not affect the deeper areas of the lake where water may already be at maximum density. At some time during this period the entire lake will reach a condition of maximum density, about 4°C. At this time vertical convective mixing ceases. As the surface temperature continues to drop, the less dense colder water remains at the surface except for such mixing as may result from wind or wave action. Following the winter season, the temperature increases slowly until late spring, when the whole lake again reaches the temperature of maximum density. During this latter period most of the lake is again convectively mixed. When the lake is vertically isothermal at temperatures somewhat higher than 4°C, the surface temperatures will increase rapidly until early August, resulting in a very stable stratification by the formation of a thermocline (a layer of rapid temperature decrease 10 to 50 feet thick). Ultimately, a homogeneous surface layer with temperatures of 18°C to 22°C is separated by a thermocline (10)(11) from bottom water which has temperatures close to 4°C. During the time of high stratification it is unlikely that even the strongest winds could cause complete mixing in the entire lake; only the water above the thermocline (the epilimnion) is available for thorough mixing with pollutants. Cooling of the epilimnion begins with September storms, and the thermocline weakens as the surface homogeneous layer cools and increases in depth until the whole lake becomes isothermal at about 4°C to 5°C in early December.

According to Church (10), minimum surface temperatures (between 0.5°C and 4.0°C) are reached between the middle and end of March, at which time the main body of the lake is vertically isothermal. These temperatures are lower than that producing maximum density; if such low temperatures could be found in the deepest part of the lake, then their presence would conclusively demonstrate complete vertical mixing of the entire lake volume for the year (12). (Church found them in much shallower water on the rise between Milwaukee, Wisconsin and Muskegon, Michigan.)

*A synoptic survey is a data gathering operation in which a number of ships on roughly parallel tracks take samples on the same day, thus approximating a set of simultaneous observations from the entire lake.

Dissolved oxygen (DO), for the most part, enters the water from the atmosphere. During periods of convective overturn the DO will tend to approach saturation values, but during periods of stratification DO losses below the thermocline at best will not be restored by vertical mixing. If pollutants with sufficient Biochemical Oxygen Demand were introduced into or below the thermocline, the DO concentration might drop rapidly to low levels.

Two points should be emphasized. First, the volume of water available for mixing keeps changing throughout the year, and it is not known whether the entire lake volume mixes completely; at certain seasons of a year, only the uppermost water (50 feet) may be available for diluting pollutants. Second, there is a stable density stratification for a significant portion of the year. The density of any pollutant introduced into the lake determines whether the pollutant would stay on the bottom, at intermediate depths, or at the surface.

Advection

Mixing as accomplished by turbulent motion is a term describing complex random movements involving relatively little transport of a water parcel, though a change in its pollution distribution. Advection is roughly the opposite of turbulent mixing, and refers to linear translation or gross motion of a water parcel. There are a number of possible situations between the two extremes, random turbulence and prevailing advection, and labelling a given situation with confidence may prove difficult.

Advection theory, in part, is in a more advanced state than turbulence theory; however, a situation often is so complex that it is exceedingly difficult to obtain even semi-quantitative predictions, especially in the vicinity of shore lines (13).

In Lake Michigan the wind seems to be the chief cause of advection (as well as internal turbulence, previously discussed). Tides are negligible for most purposes, having a range of some 3/100 of a foot (14). Seiches are important to advection only in restricted areas, such as the Straits of Mackinac. Precipitation minus evaporation although not known in definite detail, is small enough to be neglected in this instance. Because of the large area of a transverse cross-section of the lake, net flow-through produces very low velocities of advection; indeed, flow in the Straits of Mackinac is often reversed by seiches and wind-tilt. Church (10) noted that during most of the year denser water was in the center of Lake Michigan and less dense water at the edges, implying a slow

counterclockwise density circulation superimposed on the net flow-through. Project personnel found a similar distribution off Chicago in the fall of 1962. Attempts to obtain definite evidence of a stable circulation pattern have produced conflicting results. The most important works were a three-year drift-bottle study by Harrington (15), a two-year drift-bottle study by Johnson (16), and the four synoptic cruises by Ayers (11). According to Ayers (11), major current changes caused by the wind are often superimposed on the more stable, slower flow, and changing winds are responsible for the varying currents observed.

Haines and Bryson (17) find that the speed of a surface current is 1.3% of that of the wind producing it, provided the wind speed is less than 5.9 m/sec. (13 mph); above this critical speed, the relationship is believed to be non-linear. Shulman and Bryson (18) find that the direction of surface transport is about 20.6° to the right of the wind direction and that the "depth of frictional influence" is between 1.8 and 3.3 meters. These studies were conducted on Lake Mendota at Madison, Wisconsin and may not be entirely applicable to Lake Michigan. In the discussion of thermal structure it was pointed out that the thermocline separated the homogeneous less-dense epilimnion from the denser homogeneous bottom water. Bryson and Bunge (19) find that when the wind suddenly drops or shifts direction after set-up is established, a rapid increase in current velocity is observed just above the thermocline. They consider this current to be the first swing of an internal seiche. Accordingly, significant currents may exist both at the top and bottom of the epilimnion. Lathbury, et al. (20) found significant currents below the thermocline also, which they consider attributable not to seiches but to thermally and/or wind induced pressure gradients. Set-up causes a hydrodynamic pressure gradient, resulting in currents along or perpendicular to the shore. Shoreline and bottom topography will also influence currents. It is evident because of the multiple forces to be considered that attempts to predict currents soon become complicated.

Recent studies have shown that currents exist through the entire vertical column of water at least to 120 feet. Current velocities of 0.3 ft/sec at a depth of 120 feet were measured by the Project about 25 miles NE of Chicago in October 1961 (Figure 2).

On one occasion Project personnel found floating pollutants in the vicinity of Chicago's beaches and water intakes (Figure 3) for several days running (21). Generally speaking, surface currents are weak and southbound near Lake Michigan's west shore but narrower,

stronger, and northbound near its east shore. Sometimes there is evidence of a counterclockwise eddy in the lake's southern basin. Again, it is to be emphasized that these conditions are variable.

Meteorology

The winds, precipitation, and evaporation over Lake Michigan have rarely been measured. One study "Report on Wind Velocities at the Lake Crib and at Chicago" by Hazen (1883) was one of the few works undertaken to determine the wind differential that exists between the land and the lake (22). Major Ira Hunt, U.S. Lake Survey, working on Lake Erie, made some calculations on the wind differential that exists over that lake. From this study it would appear that winds over Lake Michigan can be 96 per cent greater than those over the City of Chicago at certain times of the year, according to Hunt (23).

Evaporation and precipitation over the lake surface is limited to estimates by the U.S. Lake Survey rather than precise observation information. Information from radar studies of precipitation variations over the Great Lakes are still in the experimental stage by both the U.S. and Canadian Weather Bureaus. Verber reports that convectional type rainfall over Lake Erie is less than at adjacent land stations (24). The U.S. Lake Survey has embarked on a similar study in northern Lake Michigan, and the results are now complete (25). Estimates on evaporation have varied from 21 inches per year to more than 30 inches per year. Estimates on precipitation have also varied in the same range. The U.S. Lake Survey (1960) states that the average annual precipitation over Lake Michigan (1900-1960) is 30.4 inches.

Information on precipitation and evaporation are far from insignificant when trying to determine the water balance of the lake. Wind studies are an important facet of the understanding of the currents within the lake. The meteorological factors are involved in any consideration of transport of materials that may be returned to the lake.

Possible Fate of Pollutants

Despite our present modicum of knowledge concerning current and wind conditions, one or more of the following factors can determine the fate of an effluent which is discharged into the lake. These are: a) existing current regime, b) winds, c) topography, and d) density difference between pollutant and lake water.

If there is a current regime, it will transport any pollutants introduced into it. As previously noted, there may be a counterclockwise gyre in the entire lake or an eddy in the southern portion that would be the prevailing circulation feature.

Wind sets up currents which can move pollutants introduced into the lake. The wind currents may be superimposed on any previously existing currents and may move in any direction.

Topography may determine whether a pollutant remains in an area or not. If the pollutant is less dense than lake water, then it may be moved by wind currents until it is trapped against a shore. If the pollutant is denser than lake water, it may run along the bottom to collect in depressions.

If an effluent is discharged and there is a density difference between the effluent and the lake water the following situations are possible:

1) If the effluent is of low density, it will rise to the surface and under certain wind conditions may be carried along the southern and western shores, possibly affecting adversely water supplies that serve populations totalling several million people as well as heavily used bathing beaches. Such conditions could last for many days.

2) If the effluent is of low density, it will rise to the surface and under certain wind conditions may be kept in the southern end of the lake by the eddy which is sometimes there. Under such conditions concentrations of chemical constituents well in excess of those normally present may build up.

3) If the effluent has the same density as the lake water, it will not move vertically very much. Under certain wind conditions it may be carried by subsurface currents to the Chicago water intakes or bathing beaches with little opportunity for dispersion or dilution, or brought to the surface by upwelling.

Each of the three possible situations cited above will be considerably more serious if it happens to follow a period of low wind and water currents during which effluent concentration may build up in the vicinity of diffusers. Such conditions may occur even when no ice is present and, on the basis of existing wind records, may be expected most frequently during summer months.

4) If the effluent is of high density, it will sink to the bottom and may run down to and collect in the southern basin. Concentrations of various constituents may build up and seriously interfere with existing aquatic life. The density of treated effluent may be so close to that of the lake water that at different times of year temperature changes in the lake water may result in the occurrence of all four of the possibilities listed above.

PROCEDURES

Procedures for the study are a combination of old and new techniques. These have been developed through consultation with oceanographers at the various oceanographic institutes, Chesapeake Bay Institute, Harvard University and New York University.

Included in the study period on the lake will be approximately one year of data collection. The collection of past records, experimental testing of equipment, purchasing equipment, and the development of techniques preceded the actual study and required nearly 18 months.

In order to provide the quality control of the instruments and navigation, services are secured from other agencies. The Project has established lines of liaison with the National Oceanographic Instrumentation Center to provide basic calibration of the instrumentation. Aircraft and photographic techniques used in the study of littoral currents are provided by personnel of the U.S. Naval Air Station at Glenview, Illinois. The precision for water navigation is provided by the utilization of vessels and personnel of the U.S. Corps of Engineers.

The following field procedures are now underway or are planned as weather permits.

Temperature Studies

Temperature studies on Lake Michigan have been underway since September of 1961. Approximately 20 cruises have been made on the lake since that time, with more than 200 bathythermograph (Figure 4) casts. Information gained during these studies established the various configurations of the thermocline during spring, summer, fall, and winter. Temperature information gained throughout the past year can be used to determine the depth of mixing and the variations in density layers within the lake.

In addition to securing data from bathythermographs the Project has secured 222 temperature recorders, designed by Woods Hole Oceanographic Institute, to be used in conjunction with the current meters to determine the location of the thermocline.

Tracer Methods

Drogues are being used for inshore studies. A drogue is a cloth or metal vane which is suspended in the water at any desired depth by a line which in turn is attached to a small surface float. The cross-section of the vane is sufficiently large to make the movement of the assembly dependent on forces acting directly upon the vane, with negligible effect by possibly countering forces on the line and surface float. The position of the vane below the water-surface is followed by the movements of the surface float. Drogue studies, both from a small boat and with the use of aerial photography, have been carried on in the Chicago area since the spring of 1962. The first drogue studies made by the Project were for the formulation of techniques and methods of study. Drogues will be used primarily to study current patterns in shallow water.

Other tracer techniques include the use of dye studies. Rhodamine B dye can be traced by use of a fluorometer and its concentration plotted by a recorder attachment. The Project staff has cooperated with the City of Milwaukee in making its equipment and technical advice available to the City for studies in Milwaukee Harbor. Dye tracing techniques are being planned in conjunction with the drogue study.

Fixed-Position Current Metering

Since October 1961, a study and evaluation of three types of meters have been made. These include the telemetry current meter, the Woods Hole meter, and one devised by the Marine Advisers, Inc. After an overall evaluation it was decided that the most economical and reliable approach to the study would be the use of the Woods Hole current meter. Because of a lack of testing and available information on long-term use, the Marine Advisers' current meter system was not considered.

The present current meter stations are located principally in southern Lake Michigan and were set prior to the severe winter weather. The first series of stations were set and placed in operation during the last week of November 1962.

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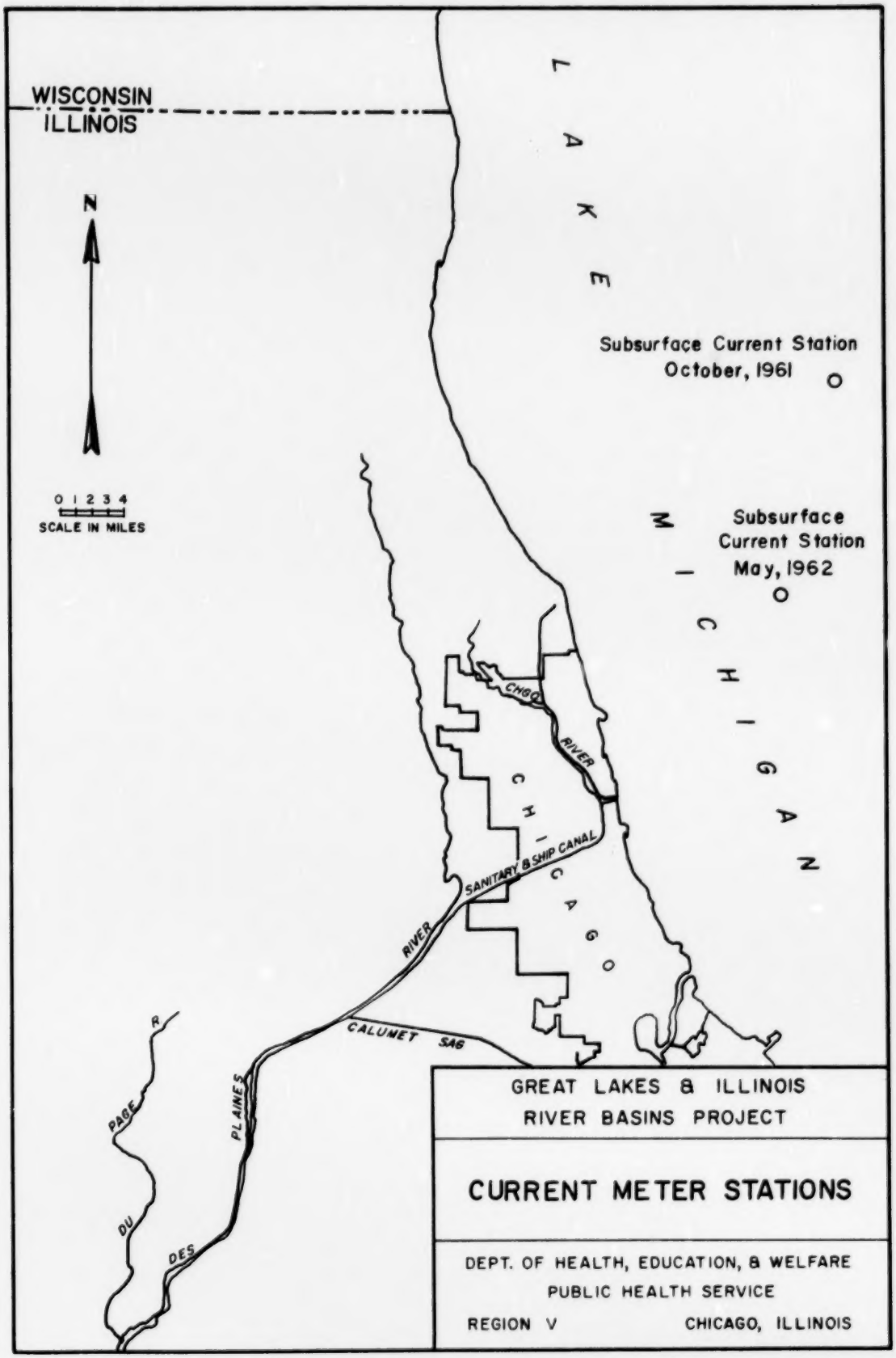
GREAT LAKES & ILLINOIS
RIVER BASINS PROJECT

DRAINAGE BASIN
of
LAKE MICHIGAN

DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 1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Subsurface Current Station
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Current Station
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SANITARY & SHIP CANAL
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CALUMET SAG
PLAINES
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DU
DES
GREAT LAKES & ILLINOIS
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CURRENT METER STATIONS
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REGION V
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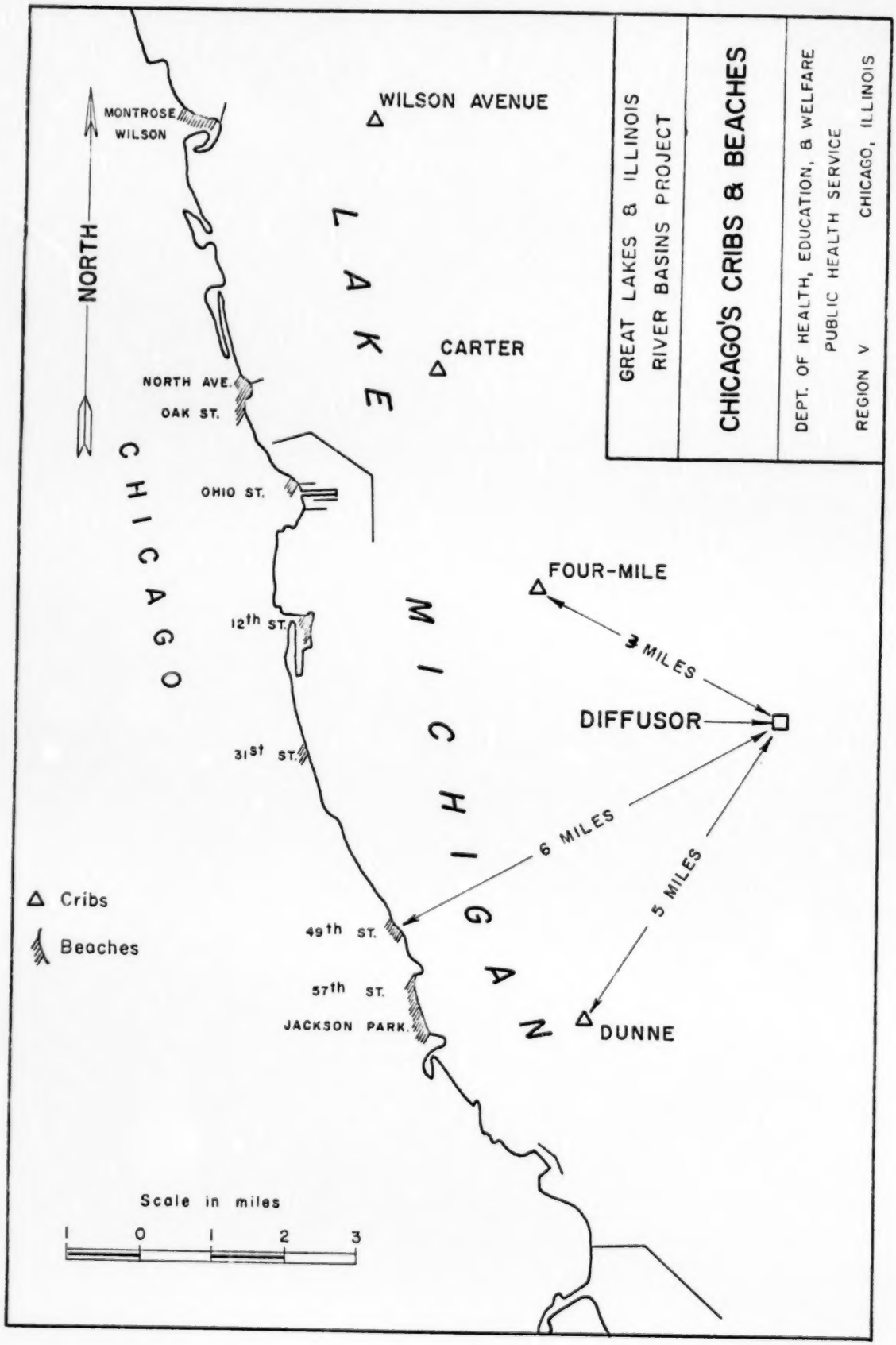
FIGURE 2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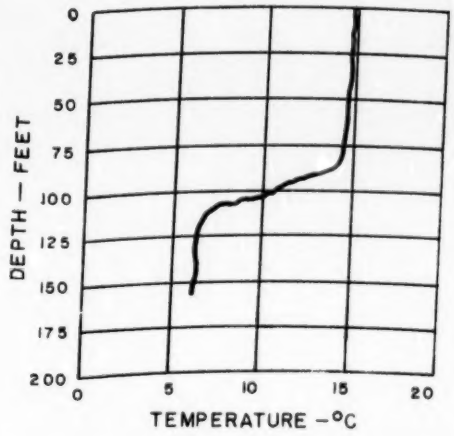
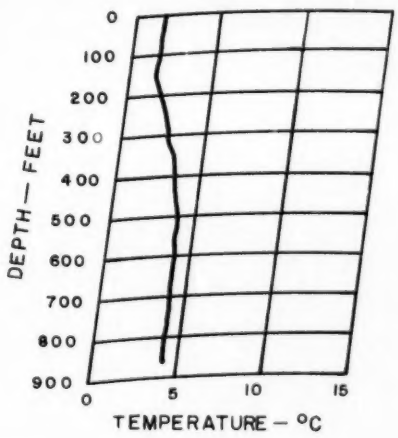
RIVER BASINS PROJECT
CHICAGO'S CRIBS & BEACHES
DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS
NORTH
MONTROSE
WILSON
WILSON AVENUE
CARTER
NORTH AVE.
OAK ST.
OHIO ST.
12th ST.
31st ST.
49th ST.
57th ST.
JACKSON PARK
LAKE MICHIGAN
CHICAGO
FOUR-MILE
3 MILES
DIFFUSOR
6 MILES
5 MILES
DUNNE
Cribs
Beaches
Scale in miles
1 0 1 2 3

FIGURE 3



*Slide No. 5
Oct. 6, 1961
Time: 1212 CST
BT No. 5834

TYPICAL SUMMER THERMOCLINE IN LAKE MICHIGAN'S SOUTH BASIN



*Slide No. 1-4
March 22, 1962
Time: 1500 CST
BT No. 1241

TYPICAL WINTER THERMOCLINE IN LAKE MICHIGAN'S NORTH BASIN

*Reproduction Of Glass Slide From Bathythermograph

GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

THE BATHYTHERMOGRAPH SLIDE

DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

GPO 827804

FIGURE 4